NBS TECHNICAL NOTE 824

A Laboratory Study of Some Performance Characteristics of an Aluminum Oxide Humidity Sensor

C
0
53
24
14
2

U.S.
TMENT
OF
MERCE
National
Bureau
of
andards

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of a Center for Radiation Research, an Office of Measurement Services and the following divisions:

Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Nuclear Sciences[2] — Applied Radiation[2] — Quantum Electronics[3] — Electromagnetics[3] — Time and Frequency[3] — Laboratory Astrophysics[3] — Cryogenics[3].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials and the following divisions:

Analytical Chemistry — Polymers — Metallurgy — Inorganic Materials — Reactor Radiation — Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute consists of a Center for Building Technology and the following divisions and offices:

Engineering and Product Standards — Weights and Measures — Invention and Innovation — Product Evaluation Technology — Electronic Technology — Technical Analysis — Measurement Engineering — Structures, Materials, and Life Safety[4] — Building Environment[4] — Technical Evaluation and Application[4] — Fire Technology.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Institute consists of the following divisions:

Computer Services — Systems and Software — Computer Systems Engineering — Information Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

Office of Standard Reference Data — Office of Information Activities — Office of Technical Publications — Library — Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Part of the Center for Radiation Research.

[3] Located at Boulder, Colorado 80302.

[4] Part of the Center for Building Technology.

A Laboratory Study of Some Performance Characteristics of an Aluminum Oxide Humidity Sensor

National Bureau of Standards
APR 29 1974

Saburo Hasegawa, Lewis Greenspan,
James W. Little, and Arnold Wexler

Mechanics Division
Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

Issued March 1974

National Bureau of Standards Technical Note 824

Nat. Bur. Stand. (U.S.), Tech. Note 824, 28 pages (Mar. 1974)

CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1974

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.46:824). Price 65 cents.

TABLE OF CONTENTS

Page

1. Introduction 1

2. Description of Sensor 3

3. Test Procedure 3

4. Results 7

5. Conclusions and Discussion 10

6. Tables 11

7. References 22

A Laboratory Study of Some Performance Characteristics of An Aluminum Oxide Humidity Sensor*

Saburo Hasegawa, Lewis Greenspan
James W. Little and Arnold Wexler

A laboratory study was made of the performance of aluminum oxide humidity sensors over a range of ambient temperatures from +20°C to -60°C encompassing dew points from +18°C to frost points of -100°C. Information was obtained on such characteristics as sensitivity, hysteresis, temperature effect, pressure-altitude effect and short-term and long-term repeatability. The sensors were found to be capable of detecting frost points as low as -100°C at ambient temperatures of -40°C and -60°C. It is estimated that the total uncertainty inherent in these sensors is approximately 4°C.

Key words: Aluminum oxide sensor; humidity; humidity sensor; hygrometer; measurement of frost points; moisture measurement; water vapor measurement.

1. Introduction

The Department of Transportation's Climatic Impact Assessment Program (CIAP) [1,2,3]** includes a global study of the nature of the stratosphere. The present distributions of temperature, constituents, motions, and circulations are being actively investigated. Among the constituents that are of concern is water vapor. Measurements of water vapor concentration in the stratosphere are or will be made with instrumentation carried aloft in balloon-borne radiosondes and in high-altitude aircraft.

The National Bureau of Standards was asked to select and study the performance characteristics of several humidity sensors for possible use in CIAP. The choice of sensors for this laboratory investigation was constrained by the following considerations. First, the sensors were required to be immediately available from commercial sources, or, at least, to have progressed to a stage of development that could make them available soon. Second, they could not exceed a cost of $350 per unit. Third, they were required to be compatible with the telemetry circuitry of the radiosonde. Fourth, they were required to have a dynamic range of three orders of magnitude in measuring humidity. Fifth, they were required to have an accuracy of about 10 percent. Sixth, they were required to have a capability of detecting moisture levels equivalent to frost points as low as -90°C. Seventh, they were required to have stable calibration curves. Finally, they were required to have a known temperature coefficient.

A survey of the field disclosed two sensors that met the criteria of immediate availability and cost and showed promise for use in the radiosonde. These were: (1) the aluminum oxide sensor and (2) the miniature crystal array. In addition this survey disclosed that there were three sensors which fell into the category of limited availability or which required further development. These were: (1) the expendable dew-point hygrometer; (2) the coated piezoelectric quartz crystal; and (3) the diffusion coulometric cell. There appeared to be no other device or sensor suitable for stratospheric moisture measurements which met the specified constraints and performance requirements, at least none that did not require extensive research and development. An evaluation program was designed to yield the following performance characteristics: sensitivity, range, hysteresis, temperature effect, pressure-altitude effect, short-term repeatability, and long-term repeatability. The tests were chosen to cover the following range of parameters: (1) ambient temperatures from 20 to -60°C; (2) dew-point temperature from 18°C to frost-point temperature of -100°C; and (3) ambient pressure-altitudes corresponding to sea level and 20 km.

The purpose of this paper is to report on the results of a laboratory investigation of two forms of the aluminum oxide humidity sensor.

---

* This work was supported, in part by the Office of Naval Research acting on behalf of the Climatic Impact Assessment Program Office, DOT, and by the Laboratory for Meteorology and Earth Sciences, Goddard Space Flight Center, NASA.

** Figures in brackets indicate the literature references at the end of this paper.

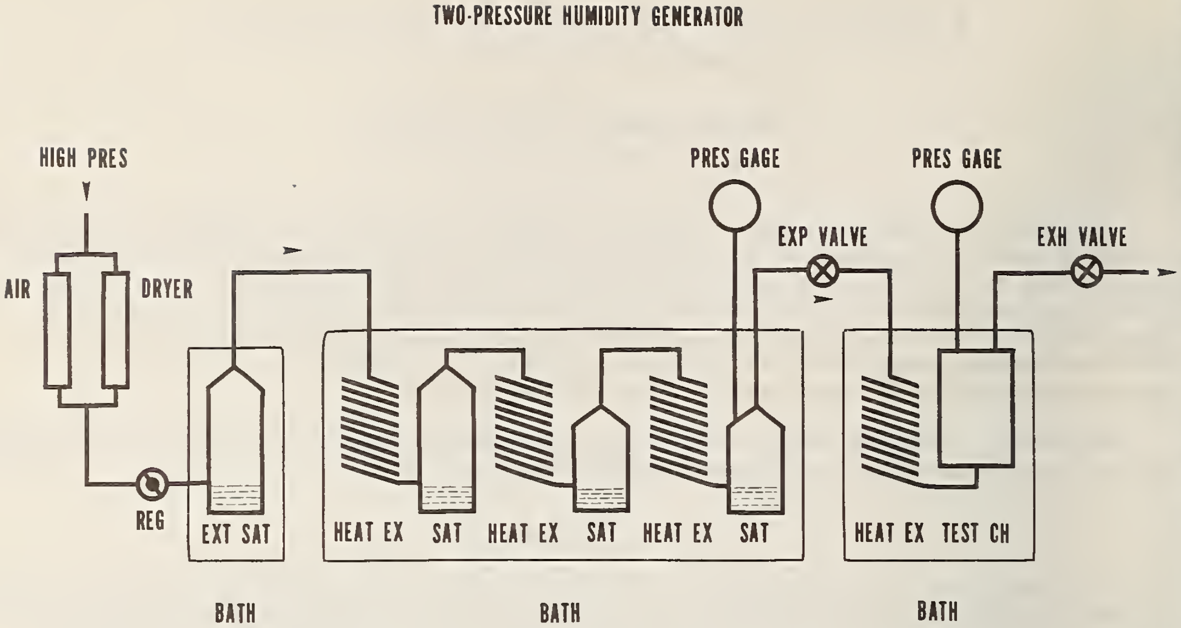


Fig. 1 Simplified flow diagram of NBS two-pressure humidity generator.

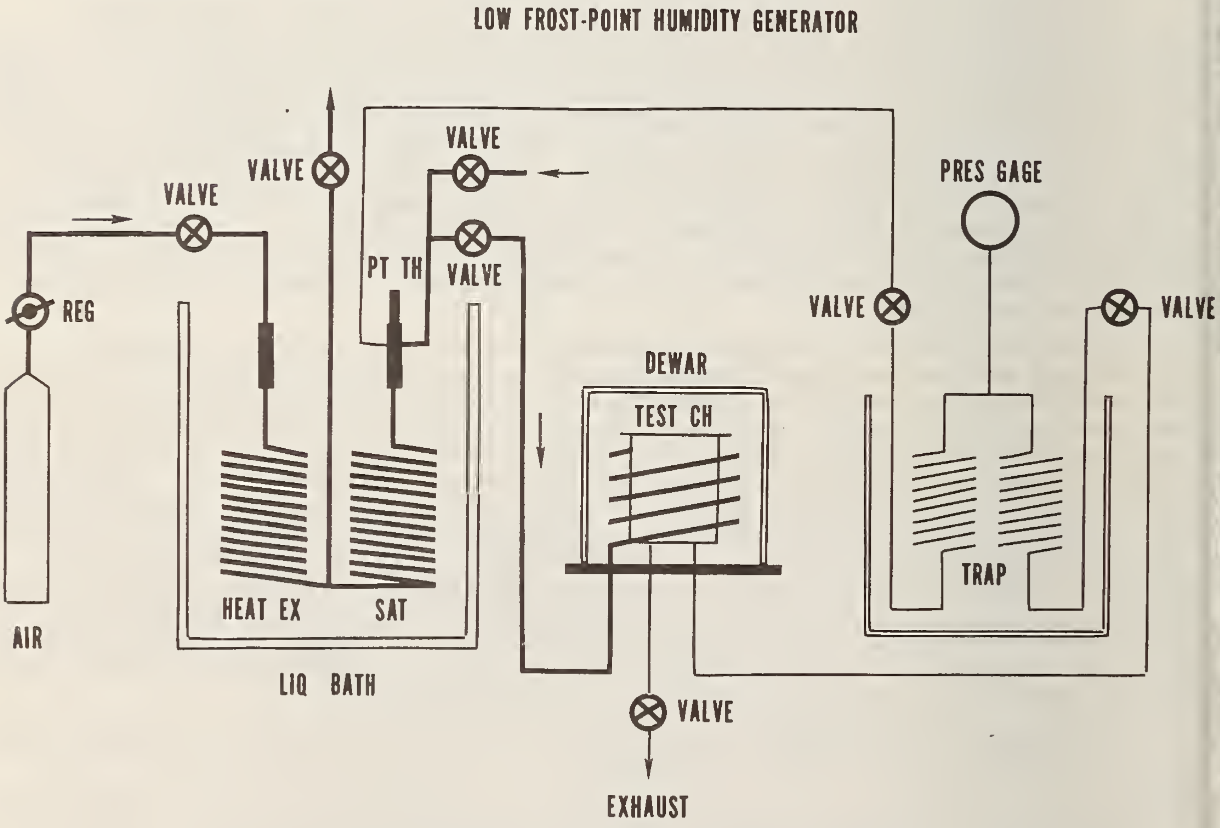


Fig. 2 Simplified flow diagram of NBS low frost-point humidity generator.

2. Description of Sensor

The aluminum oxide sensor is a variable impedance device. It consists essentially of an aluminum base or substrate with an anodized surface on top of which is a thin film of gold. The gold and aluminum serve as electrodes. Water vapor diffuses through the gold film to the oxide surface. On sorbing water vapor the oxide changes its impedance. This impedance is measured with appropriate ac circuitry.

The origin of this sensor can be traced back to the U. S. patent issued to L. R. Koller [4]. It was brought into prominence by Ansbacher and Jason [5], Jason and Wood [6], Underwood and Houslip [7], Cutting et al. [8,9], MacDowall et al. [10], Booker and Wood [11], and Jason [12]. There was further study and development work on various versions of this device by Stover [13,14], Chleck and Brousaides [15], Miyata and Watari [16], Chleck [17], Morrissey and Brousaides [18], Lai and Hidy [19], Brousaides [20], Sze [21], DelPico [22] and commercial production both in the U. S. and Great Britian.

Two forms of a commercially available sensor were used in this investigation. One was a regular or standard industrial type that has been in production for some time. The other was an experimental type which differed from the first in several fabrication details, primarily in the method of attaching electrical leads to the electrodes.

The impedance of the sensor was measured with an ac circuit which yielded a variable low-frequency output. This circuit is similar in most respects to the one used on the radiosonde. However, the latter is limited to an output of 0 to 200 hertz whereas this one can yield higher output frequencies. An electronic counter with an overall accuracy of better than 3 parts in 10^4 was used to measure the frequency.

3. Test Procedure

The National Bureau of Standards has two humidity generators which provide a capability for testing and calibrating humidity sensors and hygrometers with high accuracy. Because these generators are discussed elsewhere in great detail by Wexler and Daniels [23], Hasegawa et al. [24], Wexler [25], and Greenspan [26], only a brief description will be given here.

The NBS two-pressure humidity generator is an apparatus which produces atmospheres of known humidity. Fig. 1 is a simplified flow diagram which illustrates the principle of operation and shows the basic components. Air from a high pressure source is cleaned and dehumidified in a heatless dryer and passed through an external saturator that is temperature-controlled at 10 to 15 deg C above the desired saturation temperature. The air picks up water vapor in excess of that necessary for saturation at the desired saturation temperature. It then flows through a series of three saturators with interconnecting heat exchangers that are immersed in a temperature-controlled liquid bath. Excess water is condensed out. The gas leaves the final saturator completely saturated with vapor in equilibrium with either the liquid or solid phase (depending on the temperature) of distilled water at some fixed pressure and temperature. It now flows through an expansion valve and then into a test chamber which is located in a separate temperature-controlled bath. The pressure in the test chamber is nominally at atmospheric pressure. Measurements of the temperatures and pressures in the final saturator and in the test chamber serve to establish the moisture content of the air with high accuracy.

This apparatus is capable of generating humidities as low as -70°C in frost point. A range of ambient temperatures from +60 to -55°C can be achieved in the test chamber. The flow rate through the apparatus is maintained at 0.0014 m^3/s (84 lpm). This is equivalent to a mean air speed of about 0.02 m/s through the test chamber. The uncertainty in frost point, over most of the operating range, does not exceed 0.1 deg C.

The NBS low frost-point humidity generator also produces atmospheres of known humidity. Fig. 2 is a flow diagram which illustrates its principle of operation. Clean dry air enters a heat exchanger immersed in a liquid bath and is brought to a desired fixed temperature. It then passes through a saturator, a long helical coil of stainless steel tubing, the interior of which is coated with a thin film of ice. The path is sufficiently long so that emerging from this coil the air is completely saturated with respect to ice at the temperature of the surrounding bath. The air then flows into a gold-plated test chamber which is separately temperature-controlled. A small correction is made for the slight difference in absolute pressure between the saturator and the test chamber. The frost point produced by

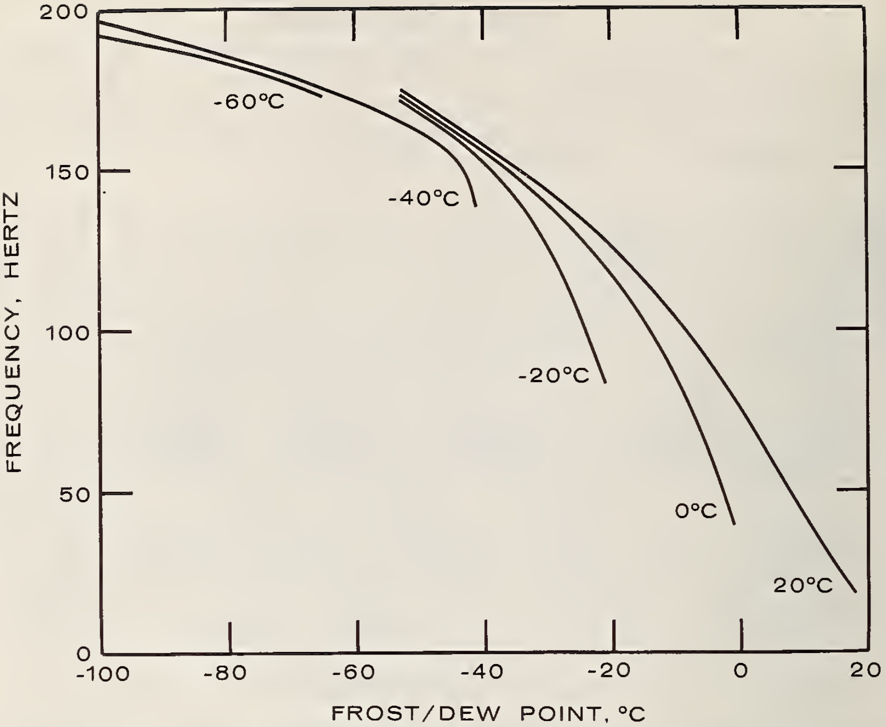


Fig. 3 Family of calibration curves (isotherms) for a typical standard sensor.

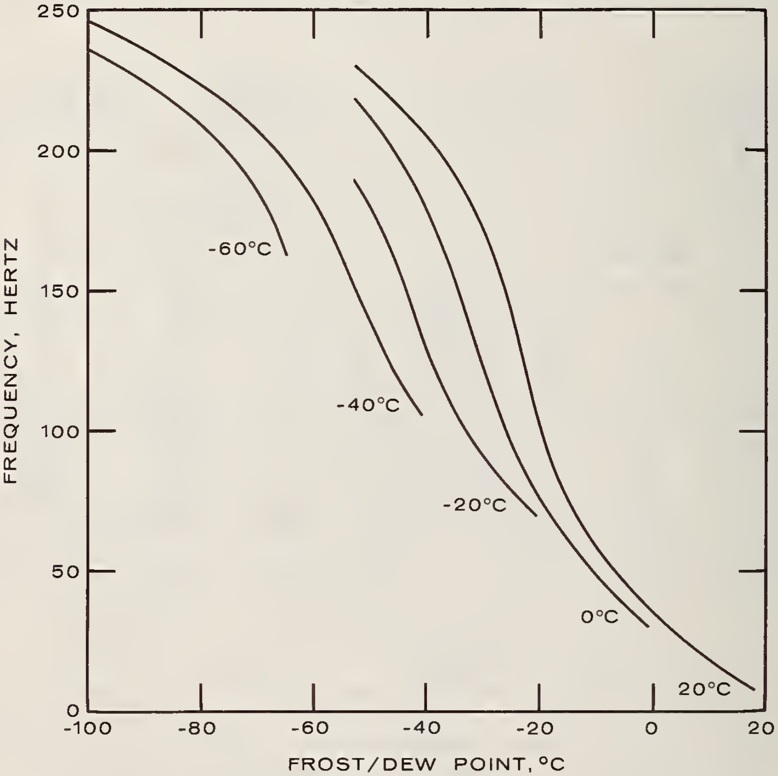


Fig. 4 Family of calibration curves (isotherms) for a typical experimental sensor.

this apparatus is basically equal to the temperature of the saturator and is measured with a platinum resistance thermometer. With this apparatus frost points from -30 to -100°C can be generated in atmospheric air and other gases. The test chamber can be operated at ambient temperatures from +25 to -100°C. Ambient pressures from atmospheric pressure to 500 Pa (5 mb) can be established within the system. The flow rate is maintained at 3.3×10^{-5} m^3/s (2 lpm). This is equivalent to a mean air speed of about 1.7×10^{-3} m/s through the test chamber. The uncertainty in frost point does not exceed 0.2 deg C.

The procedure followed in this work was to use the two-pressure humidity generator for tests at ambient temperatures from +20 through -40°C and to use the low frost-point generator at ambient temperatures of -40 and -60°C. At -40°C the operating ranges of the two generators were chosen so as to produce an overlap in the test humidities.

Ten sensors were tested simultaneously, five of the conventional industrial type and five of the modified experimental type. These ten sensors were selected by the manufacturer for use in these tests.

At each ambient temperature, a reasonable number of humidities was chosen to cover the desired test range. At each ambient temperature, the highest frost or dew point to which the sensors were subjected was chosen so that the equivalent relative humidity did not exceed 90 percent. This upper limit was set to preclude the possibility that humidities close to saturation might adversely affect the performance of the sensors. Except at the -60°C ambient temperature each test range encompassed two or more contiguous smaller spans. The ranges and spans are shown in Table 1. Within each span the sensors were cycled one or more times from the lowest to the highest frost point and then back to the initial point, except for the -55 to -100°C frost point span at the -40°C ambient temperature and the -65 to -100°C frost point span at the -60°C ambient temperature. For these latter two spans, the humidity change was made only in one direction, from the lowest to the highest frost point. In each span the sensors were exposed successively to three or more different constant humidities. After each test humidity was established readings were taken periodically until no further significant change was observed. In the two-pressure humidity generator the exposure times to reach steady state conditions at ambient temperatures of +20, 0, -20 and -40°C were 30, 40, 60 and 120 minutes, respectively. In the low frost-point humidity generator, the comparable steady state exposure times varied from 1 day to 9 days at frost points of -55 to -100°C. In changing from one test humidity to another, the sensor exhibited an initial fast response and then a slow drift to its final reading.

Response times or lags should not be inferred from these observations of exposure times. No attempt was made to differentiate between the generator and the sensor lag. Furthermore, such parameters as air velocity and sensor orientation were different in the two generators. The essential criterion governing the exposure time was the allowance of adequate time for the system (sensors and test chamber) to equilibrate after each change in humidity.

Each sensor was electrically connected to the measuring circuit through its individual shielded 2-conductor cable and a selector switch. It was noted that the output reading was affected by the length of cable, the relative positions of the separate cables, laboratory location, and stray capacitances. By keeping the circuit, cables, and surroundings in each humidity generator fixed and stable, the disturbances to the readings were minimized. Under these conditions satisfactory repeatability was obtained. Individual capacitance calibrations were made of the measuring circuit and the specific cable used with each element in each generator. These calibrations were used to adjust the output readings taken with the low frost-point generator to compensate for differences arising from the two test set-ups. The oscillator was operated only while measurements were being taken. Between measurements there was no excitation of any element.

Two sets of calibration runs were made at atmospheric pressure. The first set included the entire ensemble temperatures and spans listed in Table 1. This set comprises the initial runs. The second set was limited to ambient temperatures of 20 and -40°C. At 20°C the same four spans were used whereas at -40°C only the -41 to -53°C and -56 to -68°C frost point spans were used. This second set comprises the final runs and was made five months after the first set. After the initial runs were completed, and prior to the start of the final runs, the ten elements were calibrated at an ambient pressure of 5000 Pa (50 mb), and ambient temperature of -40°C, and over a frost-point range of -55 to -90°C at successively lower frost-point temperatures.

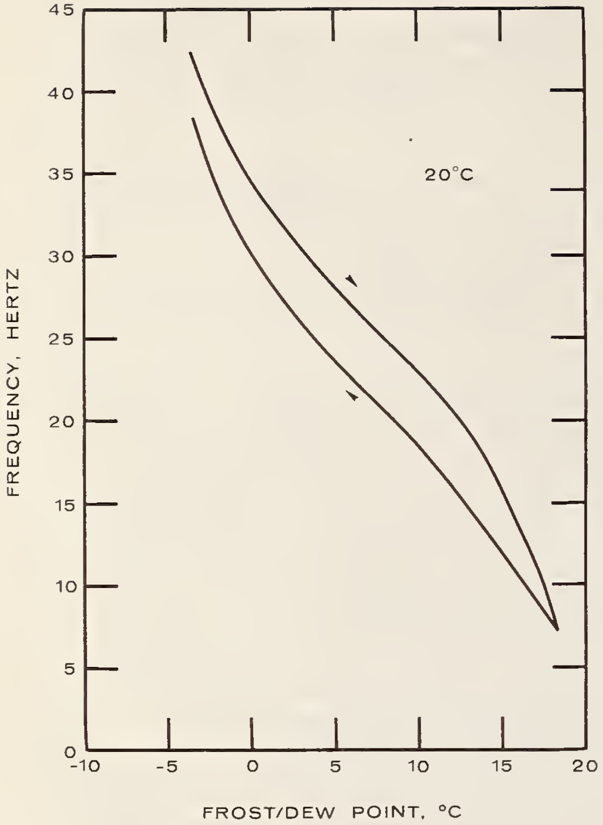
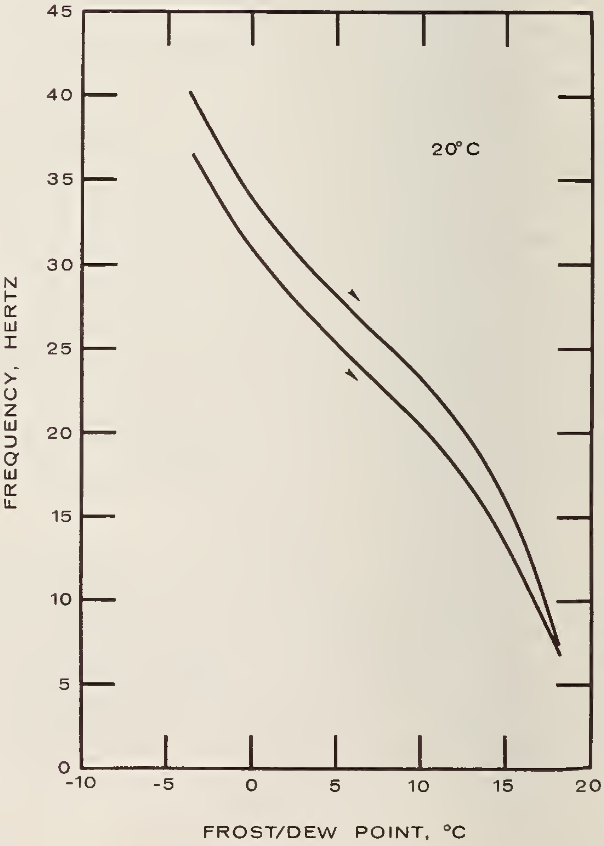


Fig. 5 Typical rested state hysteresis loop at +20°C for a span from a frost point of about -4°C to a dew point of about +18°C. The arrows indicate the direction of the humidity change.

Fig. 6 Short term repeatability. Typical plot of two calibration curves at an ambient temperature of +20°C obtained on two successive days on the same sensor.



4. Results

A family of calibration curves is shown in Figure 3 for a typical standard or conventional type of sensor and in Figure 4 for a typical experimental type of sensor. The output in hertz has been plotted as a function of frost point (below 0°C) and dew point (above 0°C) for ambient temperatures of 20, 0, -20, -40 and -60°C. For purposes of this paper, the term "frost point" will be used to refer to frost points below 0°C and to dew points above 0°C. The output frequency increases with decreasing frost point. There is a displacement of each isotherm to the left with decreasing ambient temperature. Therefore, for any given output frequency, the corresponding frost point is a function of ambient temperature. At ambient temperatures of -40 and -60°C, the sensor has sensitivity to detect humidities with equivalent frost points as low as -100°C. No attempt was made to test the sensor at frost points below -53°C at the higher ambient temperatures.

There is a tendency for the calibration curves of the standard type sensor to merge at the higher output frequencies and to diverge at the lower output frequencies. The reverse behavior occurs with the experimental type. The temperature coefficients are given in Table 2. These express the change in frost-point temperature per deg change in ambient temperature for fixed frequencies. They indicate the horizontal spread among the isotherms at a given output frequency. They can be used to estimate the error in indicated frost point due to an uncertainty in, or a failure to account for, the ambient temperature. The temperature coefficients tend to be larger for the experimental type of sensor.

The sensitivity of the sensor is shown in Table 3. An average sensitivity was calculated for each element by dividing the overall change in measured output frequency by the corresponding change in frost point for each ambient temperature. These sensitivities were pooled for each ambient temperature to yield mean values. The five mean values for each type were then combined to give a composite mean of 1.8 Hz/deg C frost point for the standard type and 3.2 Hz/deg C frost point for the experimental type. The -20°C isotherm exhibits the greatest sensitivity whereas the -60°C isotherm shows the least. The composite mean sensitivity of the experimental type is almost twice that of the standard type. For the -40°C and -60°C isotherms the ratio of sensitivities is 2.4 and 3.7.

A typical hysteresis loop for a span extending from a frost point of about -4°C to a dew point of +18°C at an ambient temperature of +20°C is shown in Figure 5. This loop was obtained without prior humidity cycling over the +18 to -4°C dew or frost point span at ambient temperature of 20°C. This first test loop will be referred to as the "first calibration cycle" obtained for the sensor for the particular dew or frost point testing span. For any output frequency the difference in frost points between the increasing and decreasing humidity branches of the loop is defined as the hysteresis. The average of the differences in frost points for equally spaced frequencies is called the average hysteresis; the maximum difference for the entire loop is the maximum hysteresis for the span. A summary of the average and maximum first calibration cycle hysteresis for each element for various temperatures and spans is given in Tables 4 and 5 respectively.

There appears to be no significant difference in hysteresis between the standard and experimental types of sensor. At each ambient temperature the hysteresis is substantially larger for the span enclosing the higher humidities (frost points) than for the spans enclosing the lower humidities. Furthermore, the hysteresis is larger at the higher ambient temperatures.

Figure 6 is a typical plot of two calibration curves covering a frost or dew point span of -4 to +18°C at an ambient temperature of 20°C. Only the increasing humidity branches of the hysteresis loops are shown. These two curves were obtained on the same sensor on successive days. Therefore, the displacement may be taken as an indication of the short term repeatability of the sensor. Shifts of this kind occur to a greater or lesser extent with each element. This short term repeatability varies with ambient temperature and span. Average and maximum values of short term repeatability are given in Tables 6 and 7. Again, there appears to be no significant difference in behavior between the two types of sensor. As in the case for hysteresis, at each ambient temperature the short term repeatability (more precisely, the lack of repeatability) is larger for the higher humidity spans than for the lowers ones; also, the shifts are larger at the higher ambient temperatures.

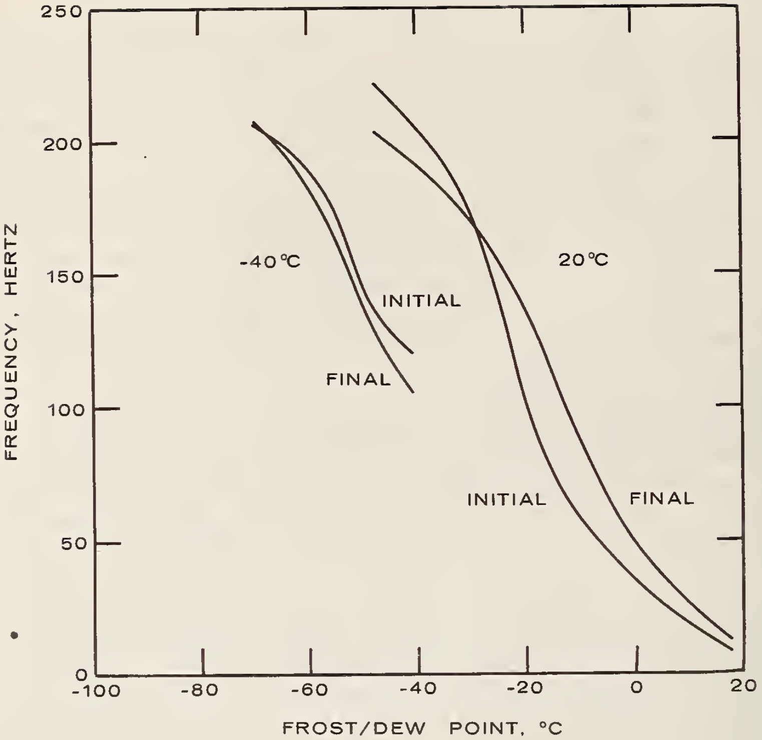


Fig. 7 Long term repeatability. Typical plot of +20 and -40°C isotherms. The "final" curves were obtained 5 months after the "initial" curves

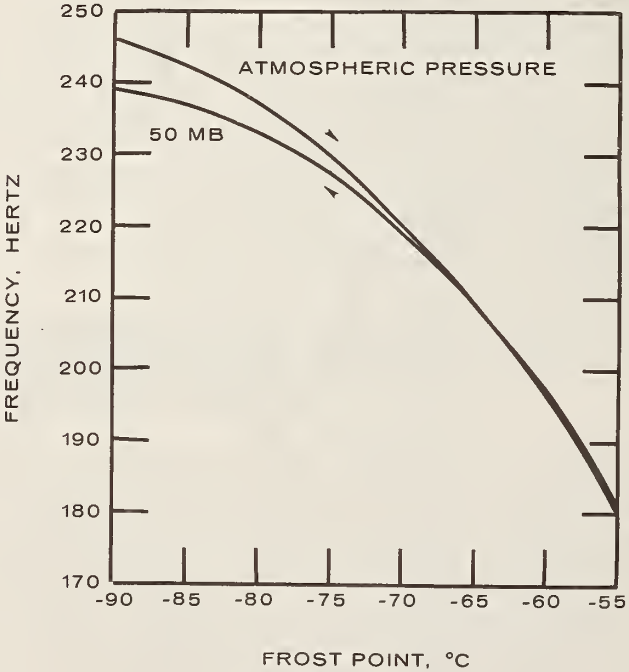


Fig. 8 Ambient pressure effect. Typical plot of -40°C isotherm obtained at standard atmospheric pressure and at 5000 Pa (50 mb). Divergence of the curves may not be significant.

Figure 7 is a typical plot of 20 and -40°C isotherms based on calibration runs made about 5 months apart. Only the increasing humidity branches of the hysteresis loops are shown. During the interval between the two runs the element had been subjected to the humidity spans and ambient temperatures outlined in Table 1 and to an ambient pressure of 5000 Pa (50 mb). The difference between these two curves may therefore be viewed as the result of the combined effect of aging, testing, cycling, etc. This difference will be defined as long term repeatability. Average and maximum values of long term repeatability are given in Table 8 for the +20 and -40°C isotherms. The long term effect is larger for the experimental type. The +20°C isotherm displays a much larger effect (from two- to three-fold) than the -40°C isotherm. The change that occurs produces both a displacement and a rotation of the isotherm, with the two curves crossing at a high output frequency.

For each element, at each ambient temperature, the calibration data were fitted by the method of least squares to a polynomial equation of the form

$$t = \sum_{i=0}^{n} a_i f^i ,$$

where t is the temperature in C of the frost point (below 0°C) and the dew point (above 0°C) and f is the sensor output frequency readings in hertz. Satisfactory fits generally were obtained for n = 3. Higher degree polynomials yielded no significant improvement in the fits. The estimated residual standard deviation σ_r was calculated for each equation using the formula given by Natrella [27]

$$\sigma_r = \left(\frac{\sum_{i=1}^{k} r_i^2}{k-j} \right)^{1/2}$$

where r_i is the difference between the experimental frost (or dew) point and the corresponding computed value, k is the number of fitted points, k-j is the number of degrees of freedom and j is the number of coefficients in the polynomial equation. The residual standard deviation will be used as a measure of estimated random uncertainty arising from the use of the element at the appropriate ambient temperature.

Table 9 gives the values of σ_r for the initial runs. There appears to be a tendency for the residual standard deviation to be larger for the standard type of sensor, except for the 20°C isotherm. At -40°C the mean σ_r for the standard type is 2 times larger than for the experimental type over the -41 to -68°C frost point range and 3 times larger over the -41 to -100°C frost point range. No data were obtained at frost points below -53°C at the ambient temperatures of 20, 0, and -20°C. Therefore, it is not known whether frost points below -53°C would increase the σ_r of these isotherms as it did for the -40°C isotherm. The overall mean σ_r for the five isotherms is 1.5 and 1.3 deg C, respectively for the standard and experimental types of sensor.

The final runs only cover two ambient temperatures: +20 and -40°C. Furthermore, as indicated earlier, the -55 to -100°C frost span was not included in the +20°C runs. Therefore, this span was deleted from the initial runs at -40°C and a new σ_r calculated. The residual standard deviations for the ensuing initial and final runs are compared in Table 10. The values of σ_r for the final runs tend to be larger than for the initial runs.

The hysteresis observed in the elements during the final runs was larger in magnitude than in the initial runs. Table 11 summarizes the average and maximum hysteresis encountered during the final runs.

The typical effect of a change in ambient pressure on the -40°C isotherm is shown in Fig. 8, over the frost-point range of -55 to -90°C. There appears to be no significant difference between the standard atmospheric pressure curve and the 5000 Pa (50 mb) curve for frost points of -55 to -75°C. At -90°C the 50 mb curve dips substantially below the standard atmospheric pressure curve producing an apparent difference in frost point of approximately 3 to 7 deg C. However this observed difference may be due, in part or entirely, to reasons other than ambient pressure. The atmospheric pressure curve represents data taken in the increasing humidity direction, whereas the 50 mb curve represents data taken in the decreasing humidity direction. Thus hysteresis may be a contributing factor. The exposure time for a change from a frost point of -100 to -90°C (at atmospheric pressure) was 7 days; for a change from a frost point of -75 to -90°C (at 50 mb) the exposure time was 3 days. Although it was assumed after these exposure times that steady state conditions were reached because of the almost negligible residual drift in the elements, it is possible that further changes in reading would have occurred with longer exposure times. If steady state conditions were not obtained then the indicated output frequency for the atmospheric pressure curve is too high (since the frequency change was from a higher to lower value) and the indicated output frequency for the 50 mb curve is too low (since the frequency change was from a lower to a higher value).

5. Conclusions and Discussion

Several basic differences between the standard and experimental types of sensor emerge from these tests. The experimental type has greater range and sensitivity. It has larger temperature coefficients. The isotherms for the standard type tend to coalesce at the low frost points (high frequencies) and diverge at the high frost (dew) points (low frequencies). The reverse occurs with the isotherms of the experimental type. The two types perform alike with respect to such characteristics as hysteresis, short term repeatability, long term repeatability, pressure effect, and estimated overall uncertainty.

The individual sensors differ from each other in all major respects and individual calibrations are required.

At ambient temperatures of -40 and -60°C the sensor is capable of detecting frost points as low as -100°C. Tests were not made at higher ambient temperatures so it is not known whether there is a similar capability at higher ambient temperature.

The sensor displays hysteresis. It also undergoes a shift in reading on being subjected to the same monotonic short span of humidity after an elapsed time of 1 to 2 days (short term repeatability). It undergoes a larger shift in calibration after an elapsed time of 5 months (long term repeatability).

The overall mean residual standard deviation σ_r in terms of dew or frost point for the five isotherms comprising the initial run for all standard elements is 1.5 deg C and for all experimental elements is 1.3 deg C. A reasonable estimate for the overall maximum uncertaint inherent in this sensor can therefore be taken as 3 σ_r or 4.5 and 3.9 deg C for the two types of sensors, respectively. There is also a shift in calibration with time or use or both. After subjecting the sensor over a period of five months to a range of ambient temperatures of 20 to -60°C and to frost points as low as -100°C and to ambient pressures of 50 mb, the 20°C isotherm undergoes an average shift of 5.1 and 6.0 deg C in dew or frost point and a maximum shift of 8.5 and 12.1 deg C for the standard and experimental types, respectively, whereas the -40°C isotherm experiences average shifts of 1.4 and 2.5 deg C and maximum shifts of 2.9 and 4.9 deg C for the standard and experimental types, respectively.

It should be emphasized that the conclusions given here are based on data taken on elements that were not exposed to relative humidities above 90 percent. The data presented here indicate that conditions tending to degrade performance, such as aging, hysteresis, etc., tend to have more pronounced effects at the higher humidities. What effect, if any, exposure to conditions of saturation or near saturation would have, is not known. In addition, it is not known how representative these elements are of normal production.

Another important characteristic that was not investigated is the response time (lag). Knowledge of this property is essential for many humidity measurement applications.

A further observation may be worth adding. These tests were made under laboratory conditions where care was taken to minimize or eliminate all known sources of error. If similar precautions are not taken when these (or any other sensors) are utilized for a specific measurement problem, then additional systematic errors may be introduced. For example, in stratospheric measurements using balloon-borne instrumentation such factors as moisture contamination, solar radiation, telemetry errors, shelf life, and lag can contribute large uncertainties.

Table 1

Testing Ranges and Spans

Ambient Temperature, °C				
20	0	-20	-40	-60
Overall testing range in dew/frost point[1], °C				
+ 18 to -53	-1 to -53	-21 to -53	-41 to -100	-65 to -100
Testing spans in dew/frost point[1], °C				
+ 18 to -4				
0 to -18	-1 to -19			
-20 to -36	-20 to -36	-21 to -36		
-40 to -53	-40 to -53	-40 to -53	-41 to -53	
			-56 to -68	
			-55 to -100	-65 to -100

---

[1] Dew point for temperatures above 0°C; frost point for temperature below 0°C.

Table 2

Temperature Coefficient

Frequency	Type of sensor									
	Standard					Experimental				
	Element No.									
	2	4	6	8	9	1	3	5	7	10
hz	Mean temperature coefficient, deg C frost point/deg C ambient temperature									
50	0.15	0.45	0.35	0.55	0.60	0.10	0.20	0.60	0.45	0.25
100	.05	.20	.15	.35	.38	.29	.38	.18	.47	.25
150	.10	.17	.10	.10	.17	.43	.42	.37	.42	.43
200						.52	.45	.38	.40	.52

Table 3

Sensitivity

Type	Element	Ambient temperature, °C					
	No.	20	0	-20	-40	-60	20 to -60
		Average sensitivity, hz/deg C frost point					
Standard	2	2.6	3.0	2.7	1.6	1.0	
	4	1.9	1.9	1.9	0.9	0.6	
	6	2.1	2.3	2.3	1.2	0.7	
	8	2.2	2.4	2.7	1.3	0.7	
	9	2.2	2.4	2.8	1.2	0.6	
	Mean	2.2	2.4	2.5	1.2	0.7	1.8
Experimental	1	3.1	3.2	3.4	2.6	2.4	
	3	3.1	3.5	3.7	2.9	3.0	
	5	3.4	3.7	3.9	2.9	1.7	
	7	3.2	3.9	5.0	3.2	2.7	
	10	2.9	3.3	2.9	2.9	3.1	
	Mean	3.1	3.5	3.8	2.9	2.6	3.2
		Experimental mean sensitivity/standard mean sensitivity					
		1.4	1.5	1.5	2.4	3.7	1.8

Table 4

Average hysteresis

First Calibration Cycle

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Average hysteresis, deg C dew/frost point											
20	-53 to -40	0.2	0.0	0.3	0.1	0.1	0.1	0.3	0.2	0.0	0.4	0.0	0.2
	-36 to -20	0.1	0.2	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0
	-18 to 0	0.6	0.3	0.4	0.3	0.3	0.2	0.3	0.2	0.4	0.4	0.5	0.2
	- 4 to 18	3.8	1.6	2.7	1.5	1.3	2.2	1.4	2.7	2.8	3.4	3.6	2.8
0	-53 to -40	0.1	0.2	0.1	0.1	0.2	0.1	0.4	0.3	0.7	0.6	0.1	0.4
	-36 to -20	0.2	0.0	0.3	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1
	-19 to - 1	2.9	2.7	2.8	2.0	2.2	2.5	1.5	1.7	0.2	1.7	2.3	1.9
-20	-53 to -40	0.2	0.6	0.1	0.0	0.2	0.2	0.2	0.2	0.4	0.2	0.4	0.3
	-36 to -21	1.0	1.1	1.1	0.8	0.9	1.0	1.1	1.0	1.1	0.8	0.8	1.0
-40	-68 to -56	0.2	0.0	0.3	0.0	0.0	0.1	0.0	0.4	1.0	0.4	0.2	0.4
	-53 to -41	0.3	1.4	0.7	0.8	0.6	0.8	1.0	0.4	1.2	1.0	0.2	0.8

Table 5

Maximum hysteresis
First Calibration Cycle
Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of Sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Maximum hysteresis, deg C dew/frost point											
20	-53 to -40	0.4	0.0	0.8	0.5	0.6	0.5	0.5	0.4	0.0	0.6	0.0	0.3
	-36 to -20	0.3	0.4	0.2	0.3	0.0	0.2	0.0	0.0	0.0	0.2	0.2	0.1
	-18 to 0	0.7	0.4	0.6	0.4	0.4	0.5	0.6	0.3	0.5	0.5	1.0	0.6
	- 4 to 18	4.6	3.4	3.7	3.2	2.2	3.4	2.4	4.5	4.6	4.7	5.5	4.3
0	-53 to -40	0.2	0.7	0.7	0.3	0.8	0.5	0.6	0.4	1.0	0.7	0.1	0.6
	-36 to -20	0.3	0.0	0.5	0.0	0.4	0.2	0.1	0.0	0.3	0.2	0.2	0.2
	-19 to - 1	3.5	3.5	3.4	2.4	2.9	3.2	2.3	2.8	3.6	3.4	3.1	3.0
-20	-53 to -40	0.3	0.8	0.3	0.0	0.4	0.4	0.3	0.2	0.6	0.3	0.1	0.3
	-36 to -21	1.6	1.9	1.4	1.0	1.2	1.4	1.5	1.3	1.2	1.4	1.0	1.3
-40	-68 to -56	0.3	0.0	0.4	0.0	0.0	0.1	0.0	0.5	1.6	0.7	0.3	0.6
	-53 to -41	0.5	2.2	0.9	1.1	0.8	1.1	1.4	0.7	1.6	1.3	0.3	1.1

Table 6

Average short term repeatability

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Average short term repeatability, deg C dew/frost point											
20	-53 to -40	0.5	0.9	0.4	0.8	0.8	0.7	0.7	0.5	0.4	0.5	0.7	0.6
	-36 to -20	0.5	0.7	0.7	0.5	0.4	0.6	0.3	0.4	0.4	0.3	0.4	0.4
	-18 to 0	0.3	0.3	0.8	0.4	0.2	0.4	0.4	0.2	0.1	0.2	0.2	0.2
	- 4 to 18	2.1	1.6	0.9	1.4	0.7	1.5	0.4	1.8	2.0	2.2	2.6	1.8
0	-53 to -40	0.4	0.7	0.8	0.5	0.8	0.6	0.5	0.3	0.4	0.4	0.5	0.4
	-36 to -20	0.4	0.5	0.5	0.4	0.6	0.5	0.2	0.2	0.3	0.2	0.4	0.5
	-19 to - 1	2.2	1.8	2.3	1.4	1.5	1.8	0.8	1.1	1.5	1.1	1.8	1.5
-20	-53 to -40	0.4	0.7	0.6	0.5	0.7	0.6	0.5	0.4	0.5	0.4	0.4	0.4
	-36 to -21	0.6	0.3	0.5	0.3	0.4	0.4	0.3	0.2	0.4	0.3	0.4	0.5
-40	-68 to -56	0.4	0.0	0.2	0.0	0.3	0.2	0.4	0.2	0.6	0.2	0.4	0.4
	-53 to -41	0.2	0.3	0.3	0.4	0.4	0.5	0.2	0.2	0.3	0.2	0.2	0.2

Table 7

Maximum short term repeatability

Initial runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Maximum short term repeatability, deg C dew/frost point											
20	-53 to -40	0.7	1.0	0.8	0.9	1.0	0.9	0.8	0.7	0.5	0.7	1.2	0.8
	-36 to -20	0.8	0.8	0.8	0.6	0.4	0.6	0.4	0.6	0.6	0.5	0.5	0.5
	-18 to 0	0.6	0.5	1.0	0.6	0.4	0.6	0.9	0.4	0.3	0.3	0.5	0.5
	- 4 to 18	3.5	5.2	1.4	4.8	3.1	3.6	0.7	3.0	3.3	3.1	4.2	2.9
0	-53 to -40	0.5	0.9	0.9	0.7	0.9	0.8	0.7	0.4	0.6	0.9	0.6	0.6
	-36 to -20	0.8	0.7	0.8	0.8	0.6	0.7	0.3	0.4	0.5	0.3	0.6	0.4
	-19 to - 1	2.7	2.4	2.7	1.7	1.9	2.3	1.3	2.0	2.5	2.3	2.8	2.2
-20	-53 to -40	0.6	1.4	1.1	0.6	0.8	0.9	0.7	0.5	0.6	0.7	0.4	0.6
	-36 to -21	1.3	0.8	1.0	0.5	0.7	0.9	0.4	0.3	0.5	0.4	0.5	0.4
-40	-68 to -56	0.6	0.0	0.5	0.0	0.4	0.3	0.6	0.3	1.2	0.4	0.5	0.6
	-53 to -40	0.4	0.6	0.5	0.6	0.6	0.5	0.7	0.7	0.9	0.4	0.3	0.6

Table 8

Long term repeatability

Comparison of initial and final runs

Type	Element No.	Ambient Temperature, °C			
		20	20	-40	-40
		Long term repeatability, frost point deg C			
		Average	Maximum	Average	Maximum
Standard	2	5.0	8.6	1.6	2.1
	4	5.0	8.5	2.7	4.4
	6	4.6	7.1	1.8	4.9
	8	5.6	8.6	0.5	1.7
	9	5.4	9.7	0.5	1.7
	Mean	5.1	8.5	1.4	3.0
Experimental	1	8.6	15.8	2.5	6.7
	3	5.8	10.7	3.0	6.5
	5	5.2	12.4	3.0	4.0
	7	4.8	10.7	3.5	6.7
	10	5.7	10.7	0.4	0.8
	Mean	6.0	12.1	2.5	4.9

Table 9

Residual standard deviations

Initial runs

Type	Element No.	Ambient temperature, °C						
		20	0	-20	-40(1)	-40(2)	-60	20 to -60
		Residual standard deviation, deg C						
Standard	2	1.5	1.2	0.5	0.6	2.9	0.7	
	4	1.3	1.1	0.7	1.9	4.1	0.8	
	6	1.3	1.2	0.5	1.0	3.3	0.4	
	8	1.4	1.0	0.9	1.3	2.5	1.1	
	9	1.4	1.0	0.9	1.2	3.2	1.3	
	Mean	1.4	1.1	0.7	1.2	3.2	0.9	1.5
Experimental	1	1.1	1.0	0.4	0.4	1.1	0.6	
	3	1.2	0.7	0.5	0.4	1.2	0.1	
	5	1.9	1.0	0.2	1.1	1.1	1.0	
	7	1.4	0.9	0.5	0.5	0.8	1.4	
	10	2.3	1.1	0.5	0.4	0.9	0.4	
	Mean	1.6	0.9	0.4	0.6	1.0	0.7	1.3

(1) Based on two frost-point spans: -41 to -53°C and -56 to -68°C.

(2) Based on three frost-point spans: -41 to -53°C, -56 to 68°C, and -55 to -100°C.

Table 10

Residual standard deviations

Comparison of initial and final runs

Type	Element No.	Ambient temperature, ° C			
		20	20	-40[1]	-40[1]
		Initial	Final	Initial	Final
		Residual standard deviation, deg C			
Standard	2	1.5	2.0	0.6	0.5
	4	1.3	1.6	1.9	0.7
	6	1.3	1.8	1.0	1.1
	8	1.4	2.1	1.3	1.3
	9	1.4	2.0	1.2	1.5
	Mean	1.4	1.9	1.2	1.0
Experimental	1	1.1	1.9	0.4	1.0
	3	1.2	1.8	0.4	0.9
	5	1.9	2.1	1.1	3.1
	7	1.4	1.9	0.5	2.0
	10	2.3	2.0	0.4	-
	Mean	1.6	1.9	0.6	1.7

(1)
Based on two frost-point spans: -41 to -53°C and -56 to -68°C.

Table 11

Hysteresis

Final calibration runs

Ambient Temperature	Dew/Frost Point Span	Type of sensor											
		Standard						Experimental					
°C	°C	Element No.											
		2	4	6	8	9	Mean	1	3	5	7	10	Mean
		Average hysteresis, deg C dew/frost point											
20	-53 to -40	0.7	1.7	0.1	1.6	1.1	1.0	0.3	0.5	0.8	0.5	0.2	0.5
	-36 to -20	0.2	0.5	0.5	0.5	0.5	0.4	0.2	0.3	0.3	0.4	0.2	0.3
	-18 to 0	1.5	1.6	1.4	0.9	1.0	1.3	0.8	0.9	0.8	0.7	1.4	0.9
	- 4 to 18	6.0	3.7	4.8	3.1	3.7	4.3	4.2	4.2	4.3	4.4	6.7	4.8
-40	-68 to -56	1.1	0.8	0.8	1.8	1.7	1.2	1.3	1.2	5.9	4.0	-	3.1
	-53 to -41	0.3	0.8	1.4	1.1	1.3	1.0	0.5	0.7	2.8	2.4	-	2.1
		Maximum hysteresis, deg C dew/frost point											
20	-53 to -40	0.7	6.3	1.1	5.5	5.4	3.8	4.0	2.4	4.8	3.0	0.8	3.0
	-36 to -20	0.2	2.2	2.2	1.6	1.6	1.6	0.4	1.0	0.5	0.9	0.8	0.7
	-18 to 0	1.5	2.2	1.9	1.1	1.4	1.6	1.2	1.3	1.1	1.1	1.8	1.3
	- 4 to 18	8.4	6.0	7.1	4.5	6.7	6.5	5.8	7.1	6.6	5.4	10.0	7.0
-40	-68 to -56	1.8	1.8	1.5	3.9	3.4	2.5	2.5	2.2	9.4	5.8	-	5.0
	-53 to -41	0.5	1.4	2.1	1.3	1.9	1.4	2.4	2.2	4.0	3.1	-	2.9

References

[1]. Cannon, Jr., Robert H., 1971: Planning a program for assessing the possibility that SST aircraft might modify climate. *Science*, *52*, 836-842.

[2]. Grobecker, A. J., 1972a: The DOT climatic impact assessment program. *Proc. of the Survey Conference February 15-16, of the Climatic Impact Assessment Program*, A. E. Barrington, Editor.

[3]. Grobecker, A. J., 1972b: Assessment of climatic changes due to flights in the stratosphere. *AIAA 5th Fluid and Plasma Dynamics Conference*, Boston, Mass., June 26-28, AIAA Paper No. 72-658, 16 pp.

[4]. Koller, L. R., 1941: *Electric hygrometer*, U. S. Patent 2,237,006, April 1.

[5]. Ansbacher, F., and Jason, A. C., 1953: Effect of water vapor on the electrical properties of anodized aluminum. *Nature*, *171*, 177-178.

[6]. Jason, A. C., and Wood, J. L., 1955: Some electrical effects of the adsorption of water vapor by anodized aluminum. *Proc. Phys. Soc*. (London) *B68*, 1105-1116.

[7]. Underwood, C. R., and Houslip, R. C., 1955: The behavior of humidity-sensitive capacitors at room temperatures. *J. Sci. Inst*., *32*, 432-436.

[8]. Cutting, C. L., Jason, A. C., and Wood, J. L., 1955: A capacitance-resistance hygrometer. *J. Sci. Inst*., *32*, 425-431.

[9]. Cutting, C. L., Jason, A. C., and Wood, J. L., 1956: A capacitance-resistance hygrometer. *J. Sci. Inst*., *33*, 36.

[10]. MacDowall, J., Cutting, C. L., Jason, A. C., and Wood, J. L., 1956: A capacitance-resistance hygrometer. *J. Sci. Inst*., *33*, 284.

[11]. Booker, C. J. L., and Wood, J. L., 1960: Further electrical effects of the adsorption of water vapour by anodized aluminum. *Proc. Phys. Soc*., *76*, 721-731.

[12]. Jason, A. C., 1965: Some properties and limitations of the aluminum oxide hygrometer. Humidity and Moisture (A. Wexler, ed.) Vol. 1, 372-390, Reinhold Pub. Corp., New York.

[13]. Stover, C. M., 1963a: Hygrometer., U. S. Patent 3,075,385, Jan. 29.

[14]. Stover, C. M., 1963b: Aluminum oxide humidity element for radiosonde weather measuring use. *Rev. Sci. Inst*., *34*, 632-635.

[15]. Chleck, D., and Brousaides, F. J., 1965: A partial evaluation of the performance of an aluminum oxide humidity element. *Humidity and Moisture* (A. Wexler, ed.) Vol. 1, 405-414, Reinhold Pub. Corp., New York.

[16]. Miyata, A., and Watari, H., 1965: A hygrometer which utilizes an anodic oxide film of aluminum. *Humidity and Moisture* (A. Wexler, ed.) Vol. 1, 391-404, Reinhold Pub. Corp., New York.

[17]. Chleck, D., 1966: Aluminum oxide hygrometer: laboratory performance and flight results. *J. Appl. Met*., *5*, 878-886.

[18]. Morrissey, J. F., and Brousaides, F. J., 1967: Comments on "Aluminum oxide hygrometer: laboratory performance and flight results." Chleck, D. Reply. *J. Appl. Met*., *6*, 965-969.

[19]. Lai, J. R., and Hidy, G. M., 1968: Microsensor for measuring humidity. Rev. Sci. Inst., *39*, 1197-1203.

[20]. Brousaides, F. J., 1968: An evaluation of the aluminum oxide humidity element. *Air Force Cambridge Laboratories*, Report AFCRL-68-0547, Oct., 45 pp.

[21]. Sze, Min-nan, 1970: On the anodized aluminum humidity sensor. *Air Force Cambridge Research Laboratories*, Report AFCRL-70-0395, 30 June, 274 pp.

[22]. DelPico, J., 1967: Performance of thin film humidity sensors. *Air Force Cambridge Research Laboratories*, Report AFCRL-67-0543, 15 October, 65 pp.

[23]. Wexler, A., and Daniels, Jr., R. D., 1952: Pressure-humidity apparatus. *NBS J. Res*., *48*, 269-274.

[24]. Hasegawa, S., Hyland, R. W., and Rhodes, S. W., 1965: A comparison between the National Bureau of Standards two-pressure humidity generator and the National Bureau of Standard hygrometer. Humidity and Moisture (A. Wexler, ed.), Vol. 3, 455-459, Reinhold Pub. Corp., New York.

[25]. Wexler, A., 1968: Calibration of humidity-measuring instruments at the National Bureau of Standards. Trans. ISA, 7, 356-362.

[26]. Greenspan, L., 1973: Low frost-point humidity generator. J. Res., Vol. 77A, No. 5, Sept.-Oct.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBS TN-824	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE A Laboratory Study of Some Performance Characteristics of An Aluminum Oxide Humidity Sensor.	5. Publication Date March 1974
	6. Performing Organization Code
7. AUTHOR(S) Saburo Hasegawa, Lewis Greenspan, James W. Little, Arnold Wexler	8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234	10. Project/Task/Work Unit No. 2130430
	11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* Department of the Navy Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217	13. Type of Report & Period Covered Final
	14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A laboratory study was made of the performance of aluminum oxide humidity sensors over a range of ambient temperatures from +20°C to -60°C encompassing dew points from +18°C to frost points of -100°C. Information was obtained on such characteristics as sensitivity, hysteresis, temperature effect, pressure-altitude effect and short-term and long-term repeatability. The sensors were found to be capable of detecting frost points as low as -100°C at ambient temperatures of -40°C and -60°C. It is estimated that the total uncertainty inherent in these sensors is approximately 4°C.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Aluminum oxide sensor; humidity; humidity sensor; hygrometer; measurement of frost points; moisture measurement; water vapor measurement.

18. AVAILABILITY ☒ Unlimited ☐ For Official Distribution. Do Not Release to NTIS ☐ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13.46:824 ☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 28
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price 65 cents

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts. Includes listings of other NBS papers as issued.

Published in two sections, available separately:

- **Physics and Chemistry (Section A)**

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

- **Mathematical Sciences (Section B)**

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

DIMENSIONS, NBS

The best single source of information concerning the Bureau's measurement, research, developmental, cooperative, and publication activities, this monthly publication is designed for the layman and also for the industry-oriented individual whose daily work involves intimate contact with science and technology —*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Annual subscription: Domestic, $6.50; Foreign, $8.25.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality, and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other-agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

Consumer Information Series. Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service (Publications and Reports of Interest in Cryogenics). A literature survey issued weekly. Annual subscription: Domestic, $20.00; foreign, $25.00.

Liquefied Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $20.00. Send subscription orders and remittances for the preceding bibliographic services to the U.S. Department of Commerce, National Technical Information Service, Springfield, Va. 22151.

Electromagnetic Metrology Current Awareness Service (Abstracts of Selected Articles on Measurement Techniques and Standards of Electromagnetic Quantities from D-C to Millimeter-Wave Frequencies). Issued monthly. Annual subscription: $100.00 (Special rates for multi-subscriptions). Send subscription order and remittance to the Electromagnetic Metrology Information Center, Electromagnetics Division, National Bureau of Standards, Boulder, Colo. 80302.

Order NBS publications (except Bibliographic Subscription Services) from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215